Innovative Coal Solids-Flow Monitoring and Measurement Using Phase-Doppler and Particles Scattering Technique

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Background & Objectives(1)

- Fuel flow to individual burners is complicated and difficult to determine on coal fired boilers, since coal solids are transported in a gas suspension that is governed by the complex physics of two-phase flow
- This difficulty leads to the following problems in coal-fired boilers:

  (a) Poor emission performance

  (b) Increased unburned carbon in the fly ash

  (c) Distorted oxygen profile at boiler outlet

  (d) Uneven steam temperature profiles

  (e) Flame impingement;

  (f) Increased slagging

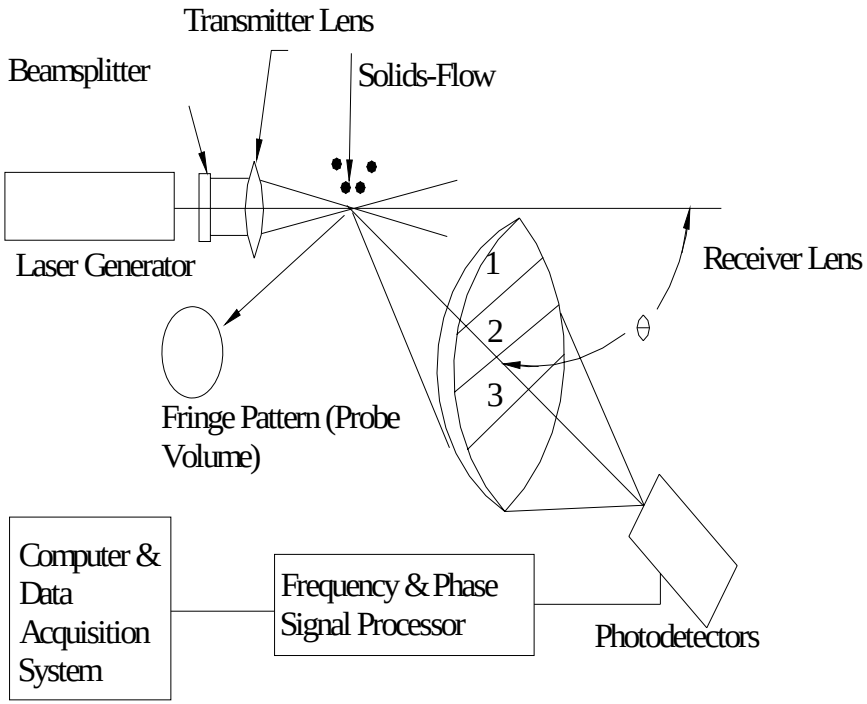
  (g) Water wall wastages.

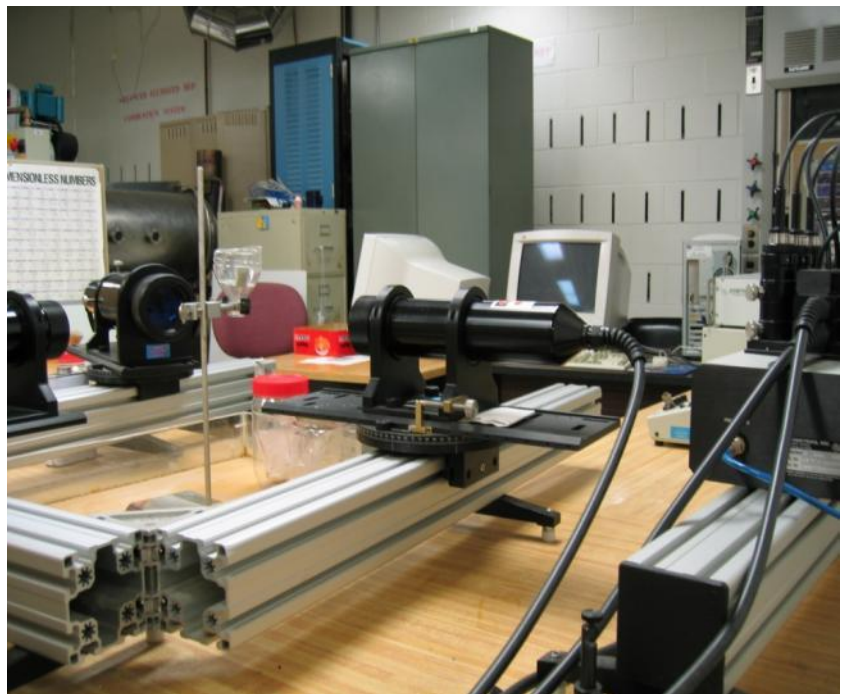
Background & Objectives(2)

- Measurements of suspended coal solids-flows are even more difficult. Various extractive methods are performed manually and can give only a snapshot result of fuel distribution.
- To measure particle size & velocity using Laser-based phase-Doppler particle analyzer (PDPA) and Particle Image Velocimetry (PIV).
- To Analyze particle characteristics using statistical method to see which factors have significant effect.

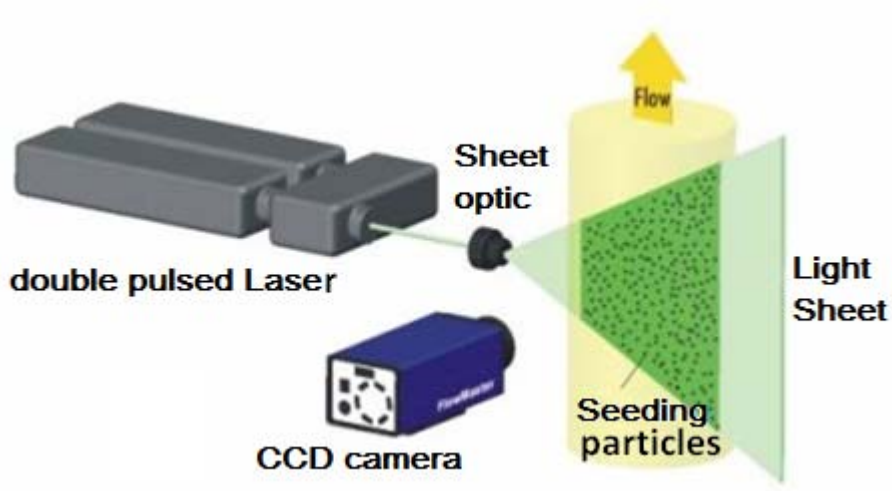
Experimental Apparatus & Procedure

- PDPA System: Particle size and velocity measurements based upon the principles of light scattering interferometry.





PIV System: an optical imaging technique to measure fluid or particulate velocity vectors at many points in a flow field simultaneously.

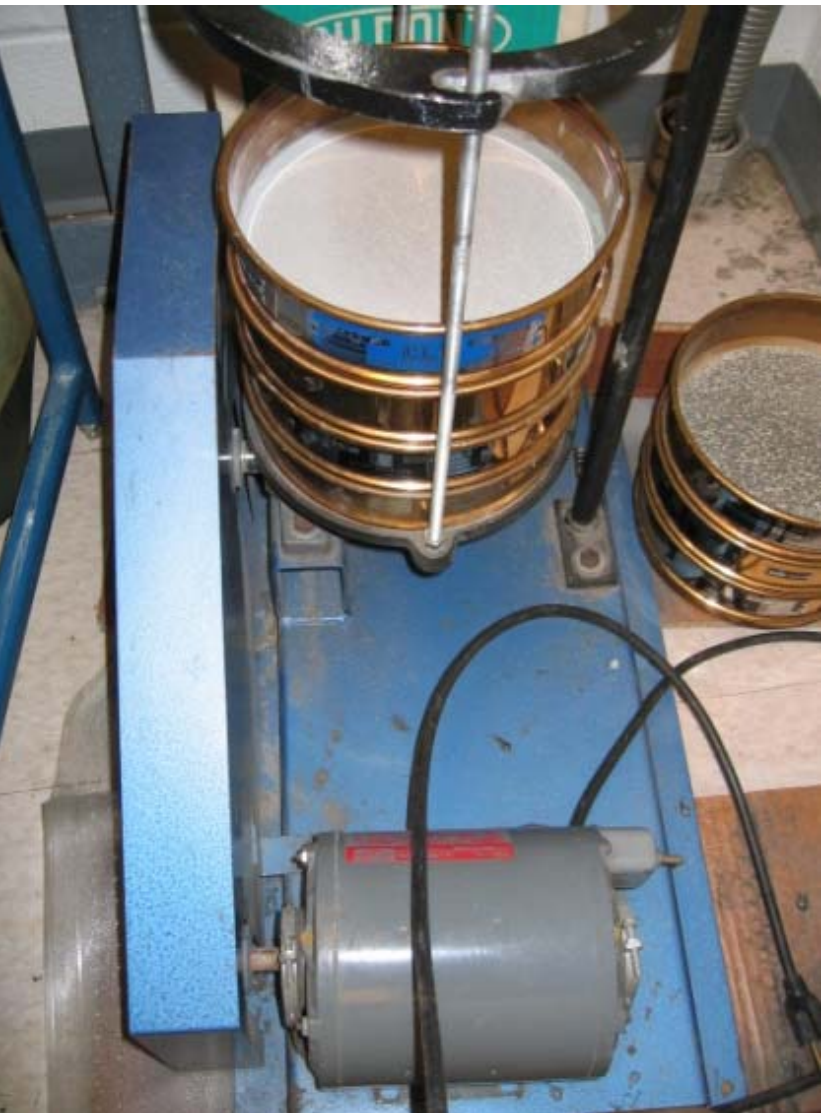


Particles Dispensing Hopper System

Humid Particle Generator

Fog Particle Generator

Solid Particles Testing Sieve System



- Summary of Tested Particles

1. Organic Particles: size <150 microns,
   150 < size < 250 microns,
   250 < size < 355 microns,
   355 < size < 425 microns,
   425 < size < 500 microns
   (Density Range: 0. 535 - 0.75 kg/dm3)
2. Potato Particles: size < 75 microns (Density: 0.9959 kg/dm3)
3. Coal Particles: size <75 microns (Density: 0.8009 kg/dm3)

(Moisture: 5.0%, Ash: 10%, Sulfur:1.50%, Heating Value: 12,000Btu/lb, Volatile Content: 35.0%, Fixed Carbon :60.0%)

Potato Particle (size < 75 microns)

Organic Particles (150 <size<250 microns)

Coal Particles (size < 75 microns)

Particle Scattering Method-related to PDPA/PIV

- When a drop passes through the intersection region of the two laser beams, the scattered light forms an interference fringe pattern.
- Since the drop is moving, the scattered interference pattern sweeps past the receiver aperture at the Doppler difference frequency, which is proportional to the drop velocity.
- The spatial frequency of the fringe pattern is inversely proportional to the drop diameter.

Mie Method (1)

- The particle size is determined from the maximum amplitude of the scattered signal using a response function based on the theory of Mie scattering from a single particle.
- This response function is coupled with a deconvolution technique incorporating the spatial variation in sample volume illumination to remove the dependence of measured sizes on particle trajectory through the measurement volume.

Mie Method (2)

- By examining a large number of particles, the size distribution can be determined.
- Practical sizing limits are dependent on the dimensions of the measurement volume and illumination intensity.
- The maximum measurable size is defined by the signal-to-noise ratio of photomultiplier.

Results & Analysis

	Coal	Potato	Organic				
			< 150 micron	150 – 250 micron	250 – 355 micron	355 – 425 micron	425 – 500 micron
1/16 0-5 cm	25.54 m/s	24.547 m/s	25.73 m/s	25.57 m/s	25.63 m/s	25.71 m/s	25.89 m/s
1/16 5-10 cm	25.579 m/s	25.258 m/s	25.78 m/s	25.49 m/s	25.73 m/s	25.76 m/s	24.57 m/s
1/8 0-5 cm	25.273 m/s	25.403 m/s	25.53 m/s	25.23 m/s	25.79 m/s	25.66 m/s	25.67 m/s
1/8 5-10 cm	25.701 m/s	25.568 m/s	25.68 m/s	25.38 m/s	25.80 m/s	25.67 m/s	25.69 m/s

Table 1. Summary of Particle Velocity Change Under different Experimental Conditions (Upper Limit)

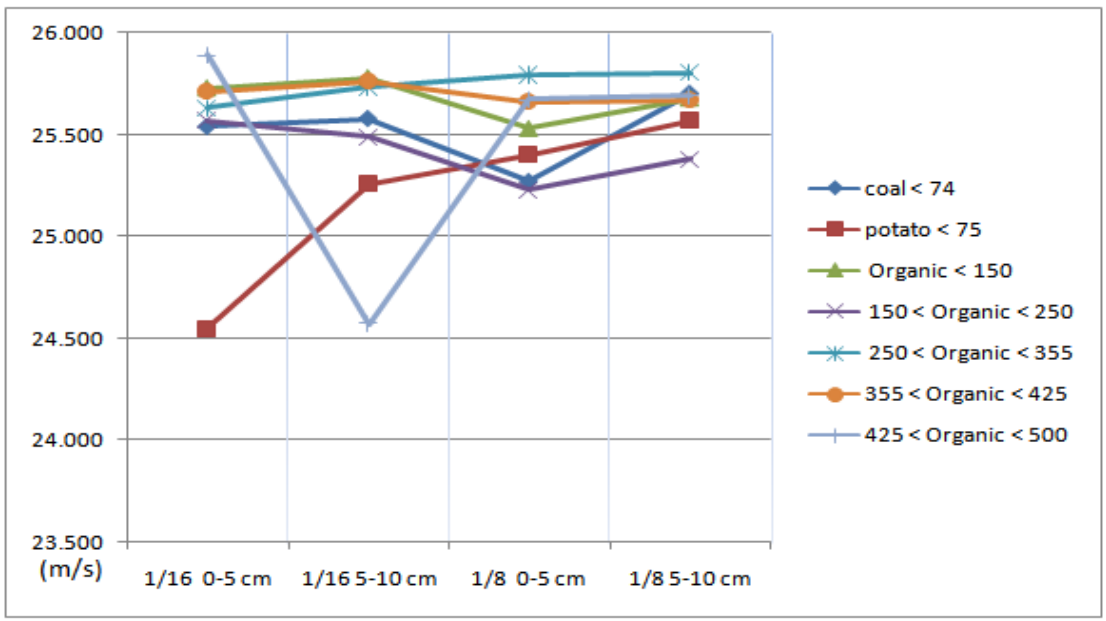


Chart 1. Summary of Particle Velocity Change Under different Experimental Conditions (Upper Limit)

	Coal	Potato	Organic				
			< 150 micron	150 – 250 micron	250 – 355 micron	355 – 425 micron	425 – 500 micron
1/16 0-5 cm	-26.479	-26.036	-26.33 m/s	-26.53 m/s	-26.67 m/s	-26.59 m/s	-24.48 m/s
1/16 5-10 cm	-26.518	-26.617	-26.3 m/s	-26.5 m/s	-26.74 m/s	-26.49 m/s	-26.77 m/s
1/8 0-5 cm	-26.416	-26.630	-28.77 m/s	-26.75 m/s	-25.25 m/s	-26.7 m/s	-25.99 m/s
1/8 5-10 cm	-26.412 m/s	-26.690 m/s	-28.38 m/s	-26.36 m/s	-25.23 m/s	-26.68 m/s	-26.59 m/s

Table 2. Summary of Particle Velocity Change Under different Experimental Conditions (Lower Limit)

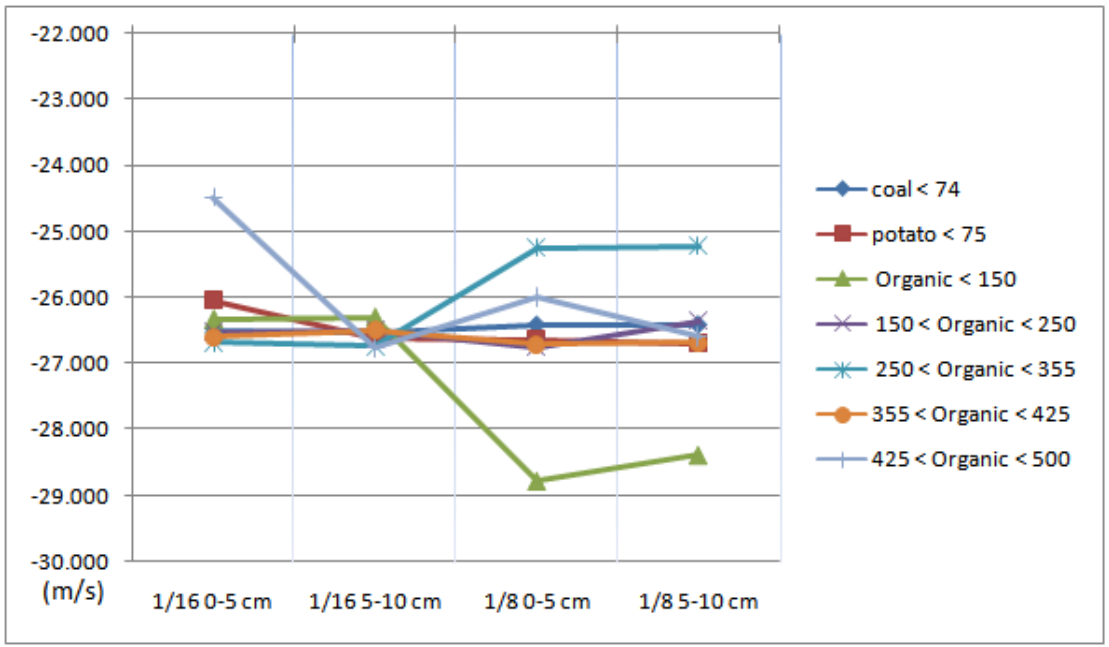


Chart 2. Summary of Particle Velocity Change Under different Experimental Conditions (Lower Limit)

Organic Particles

$$SS_{Total} = \sum_i \sum_j \sum_k y_{ijk}^2 - \frac{y_{...}^2}{abn}$$

$$SS_{Size} = \frac{1}{bn} \sum_i y_{i..}^2 - \frac{y_{...}^2}{abn}$$

$$SS_{SubTotale} = \frac{1}{n} \sum_i \sum_j y_{ij.}^2 - \frac{y_{...}^2}{abn}$$

$$SS_{Interaction} = SS_{Total} - SS_{Size} - SS_{FlowRate}$$

$$SS_{Error} = SS_{Total} - SS_{SubTotal}$$

Source of variation	Sum of Squares	Degrees of	Mean Square	F_0	P-value
Particle Size	0.35847	4	0.089617	0.99<3.48**	0.456
Flow Rate	0.00288	1	0.00288	0.03<4.96**	0.862
Interaction	0.29087	4	0.072718	0.80<3.48**	0.550
Error	0.9047	10	0.09047		
Total	1.55692	19			

Table 3. ANOVA Table for the Upper Limit of the Particle Velocity (Organic Particles)

** The values from Percentage Points $f_{\alpha,u,v}$ of the F Distribution Table

Source of variation	*Sum of Squares*	*Degrees of*	*Mean Square*	F_0	*P-value*
Particle Size	5.91965	4	1.479912	4.99 >3.48**	0.018
Flow Rate	0.5445	1	0.5445	1.84<4.96**	0.205
Interaction	7.17565	4	1.793913	6.05>3.48**	0.010
Error	2.9629	10	0.29629		
Total	16.6027	19	0.873826		

Table 4. ANOVA Table for the Lower Limit of the Particle Velocity (Organic Particles)

** The values from Percentage Points $f_{\alpha,u,v}$ of the F Distribution Table

Coal and Potato Particles

of Flow Rate Control	Observation Range	Replication1	Replication2	Replication3	Replication4	Replication5	Replication6
1/16	0-5 cm	25.7497 ~ - 26.5912 (m/s)	25.6486 ~ - 26.3219 (m/s)	25.5518 ~ - 26.6582 (m/s)	25.6788 ~ - 26.4268 (m/s)	24.9728 ~ - 26.4044 (m/s)	25.6401 ~ - 26.4705 (m/s)
	5-10 cm	25.5482 ~ - 26.3374 (m/s)	25.7059 ~ - 26.6241 (m/s)	25.4313 ~ - 26.5706 (m/s)	25.475 ~ - 26.6146 (m/s)	25.5733 ~ - 26.6724 (m/s)	25.741 ~ - 26.2907 (m/s)
1/8	0-5 cm	24.3438 ~ - 26.6708 (m/s)	24.4852 ~ - 26.3808 (m/s)	25.3971 ~ - 26.2056 (m/s)	25.4903 ~ - 26.2186 (m/s)	25.559 ~ - 26.3515 (m/s)	25.5772 ~ - 26.6709 (m/s)
	5-10 cm	25.6193 ~ - 26.6888 (m/s)	25.6582 ~ - 26.6551 (m/s)	25.7486 ~ - 26.746 (m/s)	25.5931 ~ - 26.6167 (m/s)	25.7515 ~ - 26.4668 (m/s)	25.8374 ~ - 25.3005 (m/s)

Table 5. Summary of Coal Particle Velocity Change Under different Experimental Conditions

of Flow Rate Control	Observation Range	Replication1	Replication2	Replication3	Replication4	Replication5	Replication6
1/16	0-5 cm	23.5485 ~ - 25.2168 (m/s)	23.4515 ~ - 26.8126(m/s)	24.7051 ~ - 25.5237(m/s)	25.709 ~ - 26.6757(m/s)	24.6155 ~ - 26.5592(m/s)	25.2544 ~ - 25.4284(m/s)
	5-10 cm	25.4627 ~ - 26.5766	25.274 ~ - 26.6733(m/s)	24.6679 ~ - 26.8168(m/s)	25.3959 ~ - 26.7716(m/s)	25.3706 ~ - 26.55(m/s)	25.379 ~ - 26.3116(m/s)
1/8	0-5 cm	25.3534 ~ - 26.5647(m/s)	25.4733 ~ - 26.6778(m/s)	24.8942 ~ - 26.7163(m/s)	25.7178 ~ - 26.5204(m/s)	25.6859 ~ - 26.5941(m/s)	25.2917 ~ - 26.7065(m/s)
	5-10 cm	25.7168 ~ - 26.6482(m/s)	25.6236 ~ - 26.751(m/s)	25.6312 ~ - 26.7558(m/s)	25.6386 ~ - 26.7307(m/s)	25.5087 ~ - 26.6547(m/s)	25.2916 ~ - 26.6019(m/s)

Table 6. Summary of Potato Particle Velocity Change Under different Experimental Conditions

Source of variation	Sum of Square	Degrees of	Mean Square	F_0	P-value
Type	1.0550	1	1.0550	5.84>4.08**	0.020
Open Rate	0.5934	1	0.5934	3.28<4.08**	0.078
Observation Range	1.6312	1	1.6312	9.02>4.08**	0.005
Type * Open Rate	1.5583	1	1.5583	8.62>4.08**	0.005
Type * Observation Range	0.0582	1	0.0582	0.32<4.08**	0.573
Open Rate*Observation Range	0.0005	1	0.0005	0.00<4.08**	0.960
Type*Open Rate*Observation Range	0.8519	1	0.8519	4.71>4.08**	0.036
ERROR	7.2307	40	0.1808		
Total	12.9792	47			

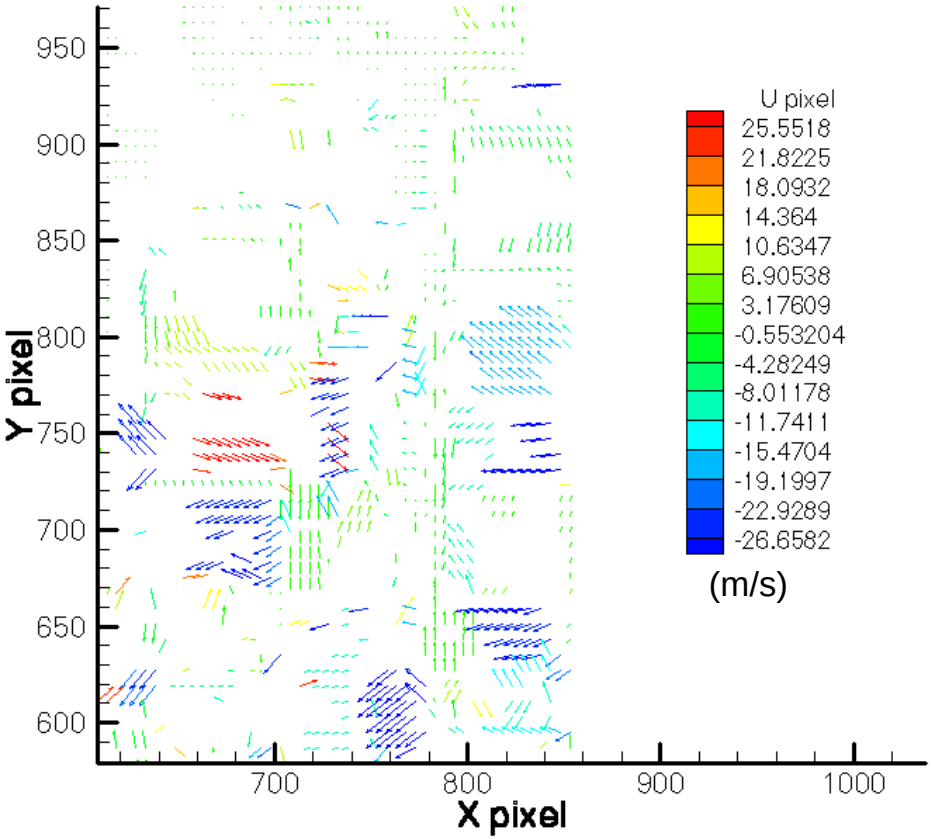
Table 7. ANOVA Table for the Upper Limit of the Particle Velocity (Coal and Potato Particles)

Source of variation	Sum of Square	Degrees of	Mean Square	F_0	P- value
Type	0.0163	1	0.0163	0.14<4.08**	0.714
Open Rate	0.1869	1	0.1869	1.57<4.08**	0.218
Observation Range	0.3432	1	0.3432	2.88<4.08**	0.097
Type * Open Rate	0.5243	1	0.5243	4.40>4.08**	0.042
Type * Observation Range	0.2750	1	0.2750	2.31<4.08**	0.136
Open Rate*Observation Range	0.2383	1	0.2383	2.00<4.08**	0.165
Type*Open Rate*Observation Range	0.1704	1	0.1704	1.43<4.08**	0.239
ERROR	4.7641	40	0.1191		
Total	6.5185	47			

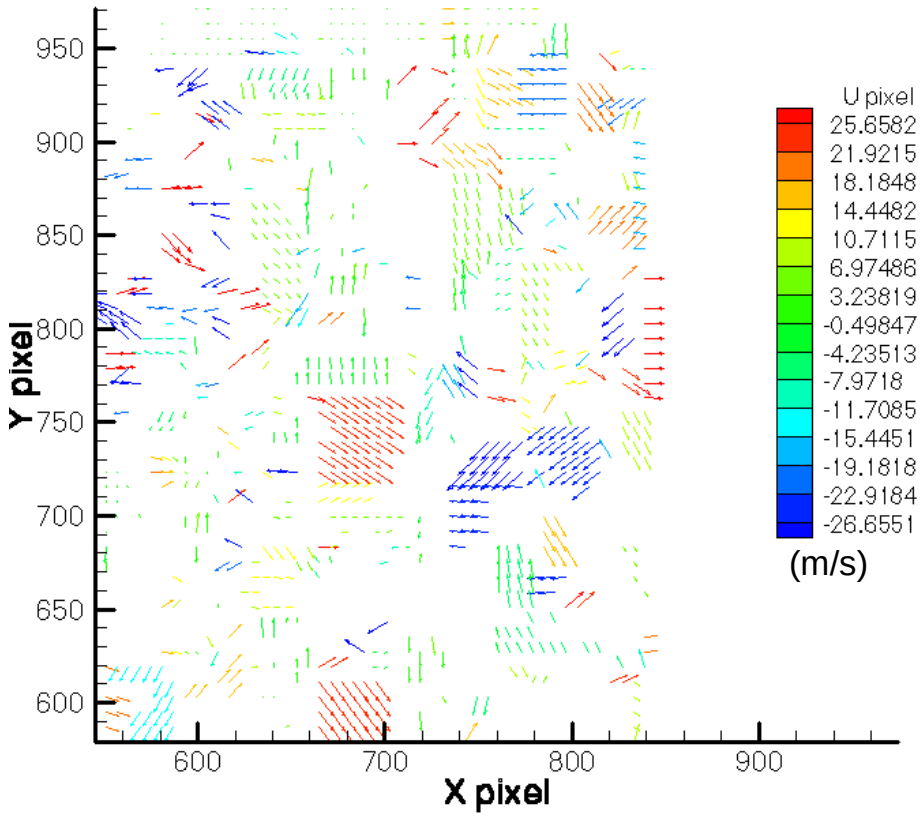
Table 8. ANOVA Table for the Lower Limit of the Particle Velocity (Coal and Potato Particles)

** The values from Percentage Points $f_{\alpha,u,v}$ of the F Distribution Table

Coal Particles

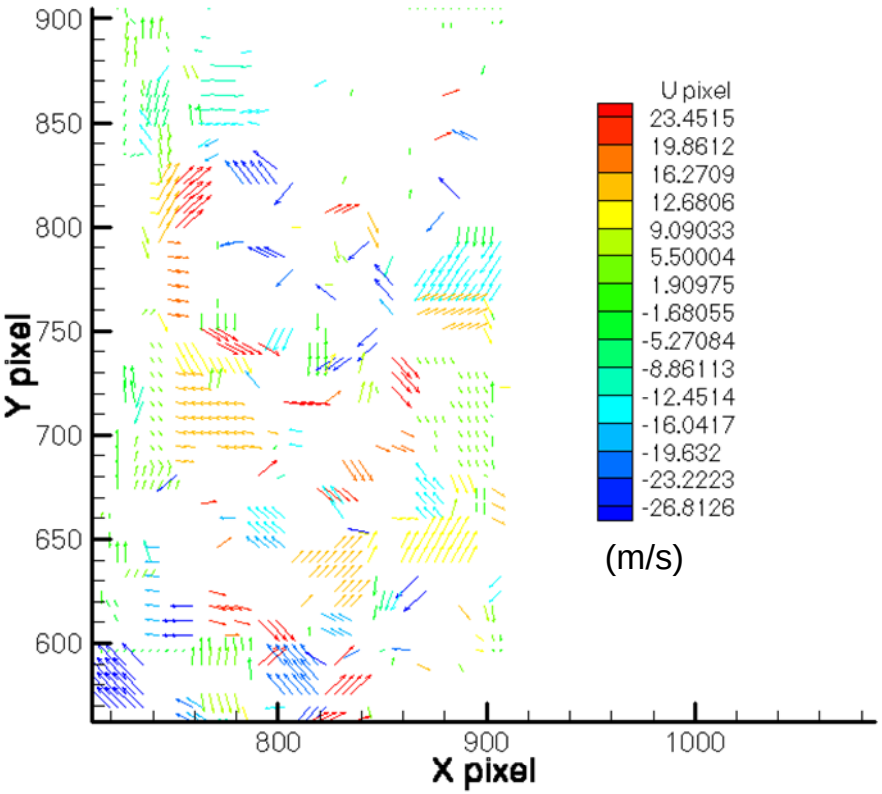


The Particle Velocity Profiles of the Coal Particles (1/16 open rate, 0-5 cm)



The Particle Velocity Profiles of the Coal Particles (1/8 open rate, 5-10 cm)

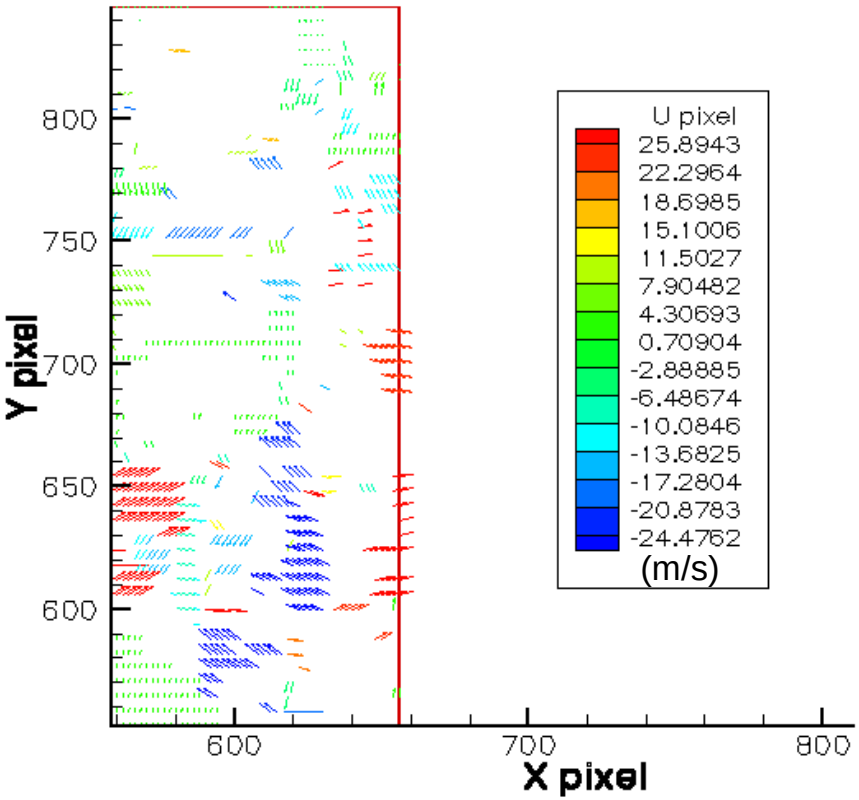
Potato Particles



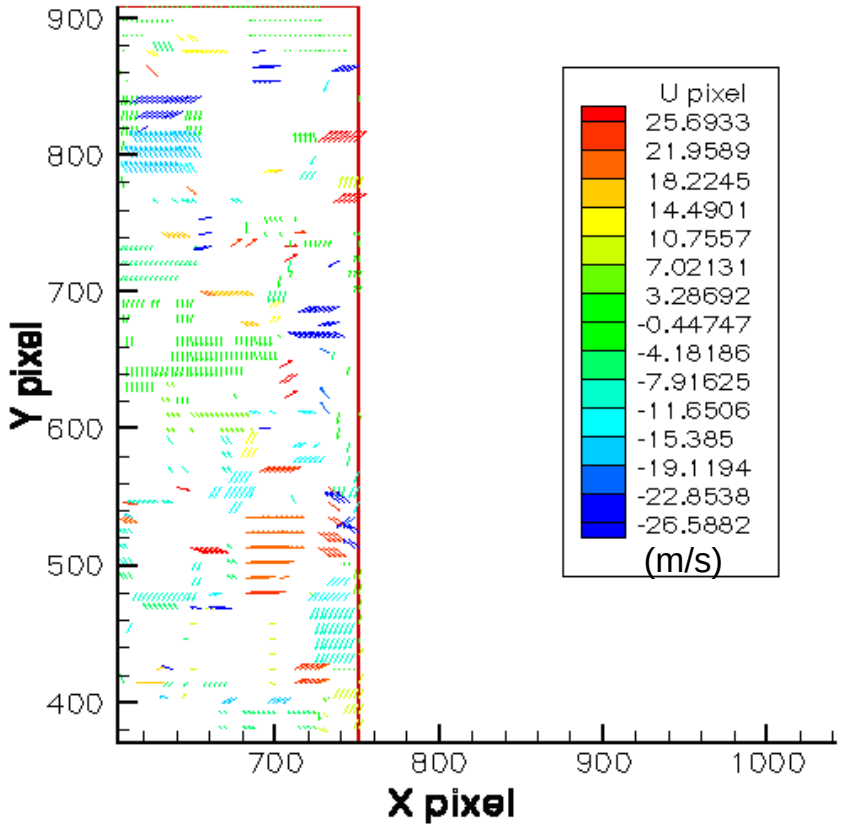
The Particle Velocity Profiles of the Potato Powder (1/16 open rate, 0-5 cm)

The Particle Velocity Profiles of the Potato Powder (1/8 open rate, 5-10 cm)

Organic Particles (425 < size < 500 microns)

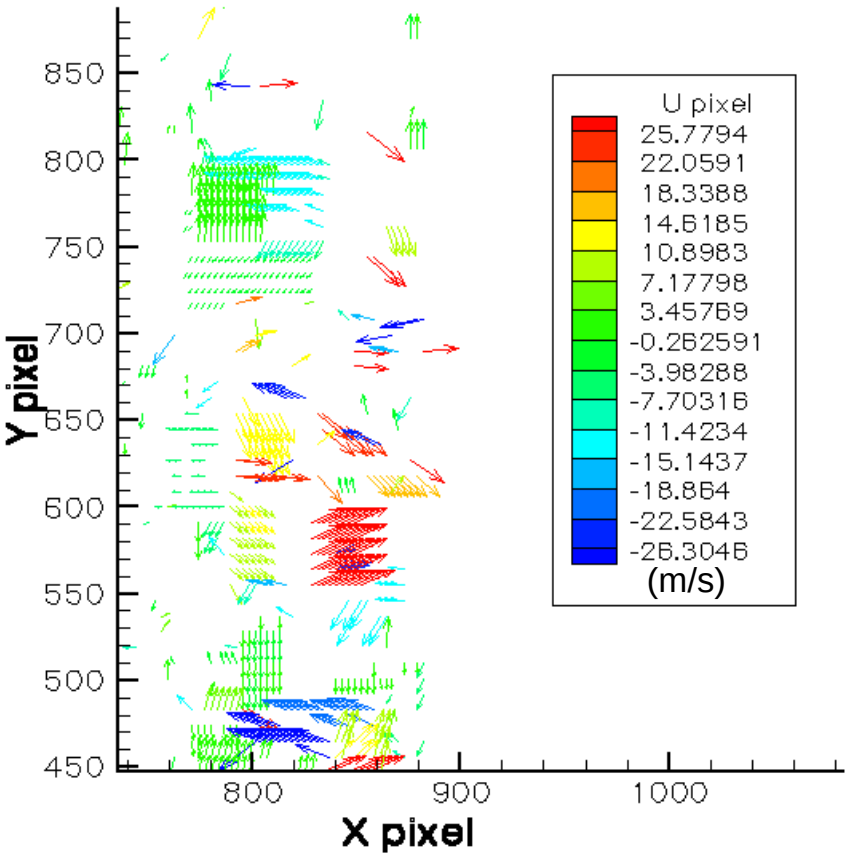


The Particle Velocity Profile of Organic Particles
(425 < size <500 microns 1/16 open rate, 0-5 cm)

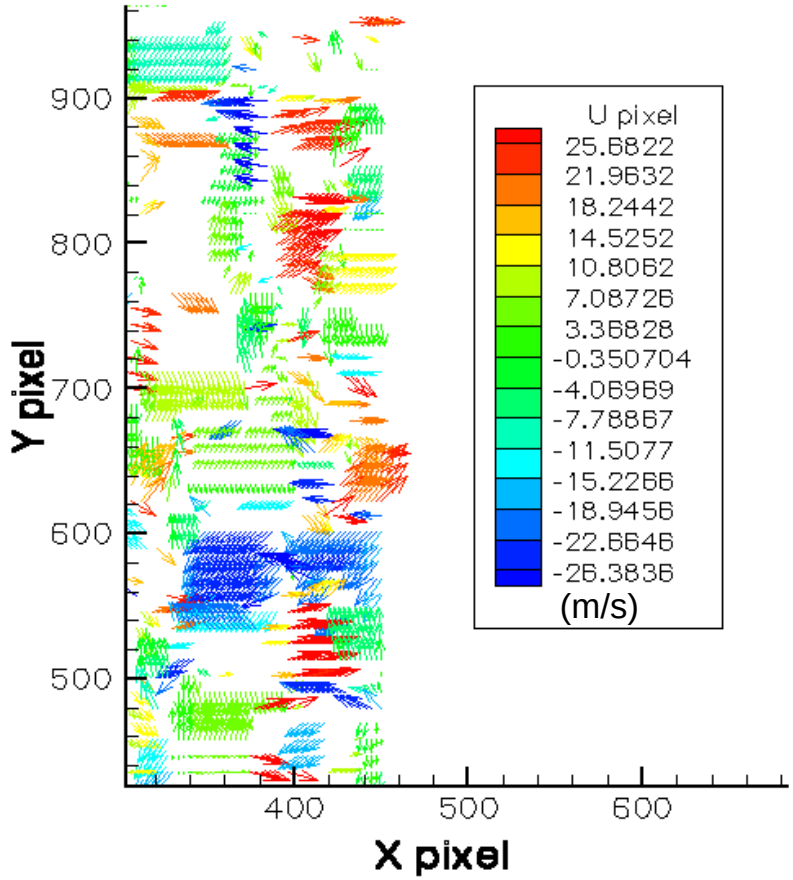


The Particle Velocity Profile of Organic Particles
(425 < size <500 microns 1/8 open rate, 5-10 cm)

Organic Particles (size < 150 microns)



The Particle Velocity Profile of Organic Particles
(size <150 microns 1/16 open rate, 0-5 cm)



The Particle Velocity Profile of Organic Particles
(size <150 microns 1/8 open rate, 5-10 cm)

Conclusions

- Laser-based PIV Instrumentation was effective to particles characterization.
- For Organic particles,

1) None of the parameters has significant effect on the upper limit of the particle velocity with 95% of confidence.

2) The particle size and interaction of particle size and flow rate have significant effect on the lower limit of particle velocity while flow rate has no significant effect on the lower limit of the particle velocity with 95% of confidence.

3)Velocity range : 25.89 ~ -28.77 m/sec

- For Coal & Potato particles,

  1) The particle type ,observation range and interaction of particle type and open rate(flow rate) have significant effect on the upper limit of the particle velocity with 95% of confidence.

  2) The interaction of particle type and open rate(flow rate) have significant effect on the lower limit of particle velocity while open rate (flow rate) and Observation range have no significant effect on the lower limit of the particle velocity with 95% of confidence.

  3)Velocity range :

  Coal -> 25.8374 ~ -26.746 m/sec

  Potato -> 25.7178 ~ - 26.8168 m/sec

Publications Related to The Project

1) Huang, Y. and S. Lee," The Advanced Instrumentation and Analysis on the Particle Characteristics using Laser-based Phase Doppler Particle Analyzer (PDPA) and Particle Image Velocimetry (PIV)" Presented and Published in the Proceedings of the 12th Annual International Conference on Industrial Engineering Theory, Applications and Practice, Mexico, November 2007.
2) Fred J. and S. Lee, "Using Laser-based Instrumentation to Give Students Experience in Advanced Instrumentation Technology" Presented and Published in the Proceedings of American Society of Engineering Education (ASEE) Middle Atlantic Conference, Philadelphia, PA. November 2007.
3) Huang, Y. and S. Lee, "Fuel Flow Simulation and Fuel Flow Characteristics Analysis in the Combustion Systems using Statistical Method", Presented and Published in the Proceedings of ASEE Middle Atlantic Conference, Philadelphia, PA, November 2007.
4) Huang. Y., S. Lee and B. Kamamia, "The Advanced Instrumentation/Analysis on The Particle Characteristics Using Laser-Based Phase Doppler Particle Analyzer (PDPA)", Presented and Published in the Proceedings of 14th Annual Undergraduate and Graduate Research Symposium, April 2007 (Awarded Second Prize).

Research Lab Staff and Participants